1.1 Foundry Future: Challenges in the 21st Century

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Introduction

The establishment of Taiwan Semiconductor Manufacturing Company (TSMC) in 1987 ushered in a new era in the electronics industry – that of the dedicated silicon foundry. The remarkable success of this innovative business model has been synergistic with the growth of the fab-less semiconductor sector, and with the economics-driven consolidation of wafer fabrication from traditional integrated device manufacturers (IDMs) to foundries. The foundry market-segment has grown to become a large integral and symbiotic part of the overall semiconductor supply-chain. There is every reason to anticipate that its importance in the supply-chain will increase further. We believe, therefore, that the continued viability of the foundry business model exerts a positive and important influence on the health of the overall IC industry.

Looking to the future, we see that maintaining historic levels of growth in the IC market will be challenging. Figure 1.1.1 shows semiconductor IC revenues since the industry's inception in 1955. Following a short period of explosive growth in the late 1950s, industry revenues increased exponentially between 1960 and 2000, with an equivalent annual average growth rate of 16%. The industry slow-down following 2000 was a watershed event: in its aftermath, the average growth rate between 2000 and 2010 is projected to reach just 6%. While projections from 2006 forward indicate that the overall market growth may increase to about 9%, it is quite clear that the growth of the overall IC market has slowed since the beginning of the 21st Century. Accordingly, it is critically necessary to scan ways whereby the foundry segment can continue to support the IC industry to maintain, or even improve growth rates. The purpose of this paper is to discuss, from the foundry perspective, the key challenges to be faced, and the business opportunities to be taken, to provide for future growth.

This paper is organized as follows: in the next section, we give an overview of the accomplishments of the silicon-foundry segment, to put into perspective its relationship to the overall semiconductor industry. In the second section we will describe the strategies we believe are necessary to ensure that the foundry segment maintains growth. Finally, in the third section, we indicate our view of the future prospects for dedicated foundries.

Foundry Accomplishments

In 1987, TSMC began to replace Integrated Device Manufacturer (IDM) foundries as the favored option for outsourced wafer production. The ensuing rapid growth of the silicon foundry segment is highlighted in Fig. 1.1.2, which shows overall revenues for the IC industry compared with total foundry revenue (IDM + Dedicated), and revenues for TSMC (as the leading example of the dedicated foundry) over the period 1987 to 2006. While the overall growth rate of the IC industry was 11%, the foundry segment showed a growth rate of 18%. TSMC, meanwhile, had an average growth rate of 43% over the same time period, demonstrating that dedicated foundries were primarily responsible for the rapid growth of foundry revenues. Today, dedicated foundries occupy over 80% of the foundry segment, while foundry revenues account for close to 12% of all semiconductor IC revenues (Figure 1.1.3, curve A). A more accurate picture of the importance of foundries to the overall IC industry, however, is provided by estimates of the value of products produced by foundries, that is, the revenue for products that are sold by foundry customers, which is also shown in Fig. 1.1.3 (curve B). By this measure, foundries now account for close to 30% of overall semiconductor revenues.

This rapid growth of the foundry segment was accomplished initially by enabling the growth of fab-less design companies, and more recently, as a result of the outsourcing of the production aspects of integrated device manufacturers (IDMs) to foundries. Underlying this rapid expansion has been the ability of foundries to provide significant value-added to their customers. Foundries have enabled rapid product innovation by providing the process technologies necessary to meet performance and cost requirements. They have also developed and enabled the user-friendly circuit-design environments needed to reduce design difficulty.

From the customer perspective, establishing foundry relationships helps to eliminate the need for the large expenditures required to develop silicon process technologies and to invest in manufacturing facilities. Moreover, for IDM companies, using foundry production as part of an overall manufacturing strategy permits flexibility in capacity allocation and optimization of internal manufacturing capabilities. The foundries themselves, meanwhile, achieve manufacturing and cost efficiencies because of the economy of scale, as well as from the larger product mix they achieve across market segments and applications. The result is better control of factory utilization at foundries; the capability to provide fast production ramp-up during initial product introduction, and flexible capacity support when demand changes. Foundries have also led the industry in cost reduction, helping their customers to retain competitive positions for their products.

Strategies for Continued Growth of the Foundry Segment

As we indicated in the previous section, the foundry segment as a whole has exhibited a higher rate of revenue growth compared to the overall semiconductor market. In this section, we will discuss the major challenges for future IC-industry growth, from a foundry perspective. We will indicate what we believe are the strategies necessary to ensure continued growth in the future:

a) Broadening CMOS Logic Technology and Adding Other Technologies

Foundries' initial growth occurred because of their successful penetration of the CMOS logic market. Projecting to the future, however, it is clear that the foundry share of this market will eventually approach high-level saturation (Figure 1.1.4).

Despite the foundries' success in the CMOS logic market, they have not yet penetrated other large IC market segments to the same extent, as shown in Fig. 1.1.5. The foundry presence in the image-sensor, microprocessor (CPU, MCU and DSP), memory, and analog markets, is considerably lower than that of CMOS logic. Strategically, foundry- service expansion is possible in all of these segments. The ability of foundries to further penetrate these markets, however, will depend on the availability of process technologies tuned to meet the cost, power consumption, and performance requirements of these markets, as well as the availability of applications where the foundry model offers a competitive advantage. These applications often require a broad portfolio of process technologies and derivative technologies (RF, mixed-signal, high-voltage, non-volatile memory, embedded-DRAM, etc.)

We believe that one of the key strategies for future foundry-business growth is to expand both into new markets for CMOS logic that are enabled by the cost reduction and performance enhancement associated with scaling, and into markets that rely on non-CMOS- based technologies, and that have not previously engaged with foundries for production. As an example of CMOS-logic-market expansion, consumer electronics will be one of the significant future growth drivers. Growth opportunities exist in cell-phone applications, game systems, digital TV, LCD displays, power management, MP3 devices, and digital cameras. Overall, the consumer-electronics market segment has its own set of challenges that foundries must meet to be successful: Product cycles for consumer items are typically rapid, and so time-to-market consider-

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ations are important. Moreover, customers will expect an increasing focus on rapid prototyping, production-cycle-time reduction, and capability for rapid wafer volume ramp-up. Advanced technology capability is also important to meet cost, power consumption, and performance objectives. These attributes are areas of relative strength for foundries. Therefore, strong foundry – customer relationships are potentially advantageous to customers' success in these product markets.

Foundries must also expand into technology segments that currently experience relatively low penetration. Foundries must broaden the range of process technologies beyond CMOS-logic. Figure 1.1.6 shows technology options now offered by TSMC as an example of the increasing breadth of services that are now available to address market segments outside of CMOS-logic, and highlights the importance of derivative technology offerings beyond CMOS-logic to address the growing image-sensor, power-management, analog-IC, and memory markets to propel future foundry growth. Furthermore, in the future, an even broader range of technology offerings, encompassing MEMS applications amongst others, can also be envisaged, as end-user markets develop.

b) Managing Design Complexity

Circuit-design complexity is increasing significantly with technology scaling. The ability to place ever-larger numbers of transistors on an individual die (Figure 1.1.7) enables increased product functionality via more sophisticated SoC designs.

As a result of increasing design complexity, the rate of introduction of new designs at foundries is decreasing for the most-advanced technology nodes, primarily because of increasingly-higher costs for IC design. Figure 1.1.8 shows estimates of increasing design costs for several process technology generations, and indicates that costs are approximately doubling for each technology generation. Additionally, prototyping costs are also now considerably increased, being driven by increasing photolithography mask cost. Consequently, only those companies with sufficient financial resources, product volume, and design capability, can undertake the required design effort during the early phase of technology introduction.

It is, therefore, vitally important that the foundry reduce design complexity for its customers by providing robust IP, design libraries, and EDA tools. It is also important that 3rd-party IP provided to the foundry is properly validated for the foundry's process technology to ensure the integrity of the final design. Moreover, frequently-used critical IP (eg USB, I/O) must be available at an early stage in the design-development cycle.

With transistor scaling into the nanometer regime, variability between devices on the silicon die is having an increasingly-marked impact on the functionality and yield of designs, and can significantly impact the capability to achieve fast production ramp-up. Designers need foundry information relating design sensitivity to manufacturing variations at an early stage of the design effort, in order to optimize their designs for maximum yield. This design-for-manufacturability (DFM) data is extracted and collected from the actual history of silicon fabrication at the foundry, and is provided in addition to the design rules and SPICE models that designers have traditionally obtained from the foundry.

To achieve an accurate DFM solution for a particular circuit design, however, requires the development of a comprehensive ecosystem for designers to accurately use DFM data. This ecosystem comprises EDA tools, IP, libraries and design-service vendors whose products and processes are certified to be compatible with the foundry DFM data. By utilizing the capabilities of this ecosystem, designers can be assured that DFM data supplied by the foundry is applied accurately to each circuit design, no matter whether the circuit-design IP is generated in-house, or supplied by a 3rd-party vendor.

With increasing design complexity, design outsourcing is now an essential option for many product designs, either to supply expertise, or to minimize design costs. To facilitate this process, it is important that the foundry establish a comprehensive portfolio of qualified design-service providers, to ensure compatibility of the outsourced IP with the foundry process technology. In this way, the foundry can also play an important role in reducing design complexity and timescale, by referring designers to service providers with the expertise to quickly resolve issues.

c) Deepening Partner Relationships

This discussion highlights the increasing importance of services provided by the foundry in ensuring successful design introduction and production ramp-up. Most importantly, we believe that the critical factor in future foundry success will be the ability of a foundry to create deeper and broader relationship with each of its customers. The role of the foundry in this relationship is to nurture an environment where customers come to consider the foundry as they would their own technology-development and manufacturing organizations, and where the foundry and customer teams are inseparably linked at all stages of the product cycle. We can express this concept simply by saying that, ideally, the customer should view the foundry as its own technology team and its own fab, but better! The ability to form such relationships with customers will be a key to differentiation of services between foundry suppliers.

This new type of relationship between the foundry and its customer is indicated conceptually in Fig. 1.1.9, and is different from previous foundry–customer relationships, in that both design and technology engineering proceed concurrently from the earliest stages of the customer's product-development effort. It is imperative that an in-depth understanding of both product and process requirements be developed as early as possible by both the foundry and its customer to ensure a successful production ramp-up, and product introduction, with less time needed for product development.

The level of information flow required for successful product introduction and volume ramp-up must go much further, well beyond provision of the layout rules and SPICE-model files traditionally supplied by the foundry, particularly for designs at the most-advanced-process technology nodes. A high level of mutual trust must be reached for this engagement to be successful, and protection of proprietary information must be assured for both parties. Because of their multiple customer relationships, particularly where customers compete within the same market segment, foundry companies need to create secure "firewalls" within their organization to protect each customer's proprietary information.

We believe that deeper, broader foundry–customer relationships offer significant advantages to foundry customers. First, early in–depth engagement allows the foundry to fully understand customer requirements for cost, power consumption, performance, and quality, and to integrate these requirements into the foundry process technology. Secondly, in developing a strong relationship with the foundry, customers can be assured of support for wafer-capacity requirements and cycle-time goals. Thirdly, customers can access the advanced design environment, including library tools and data- analysis capabilities, available at the foundry to reduce design time, and to support resolution of complex design and manufacturing-yield, or quality issues. Finally, foundries can provide a full vertically- integrated technology offering, incorporating the circuit-design environment, wafer production, and backend assembly and testing of finished product, to assure customers of successful product development, and overall faster time-to-market for their products.

d) Cost Reduction

Foundries must focus on cost reduction, with the objective of sharing the cost-savings with customers. Figures 1.1.10 and 1.1.11 indicate the costs associated with technology scaling. TSMC's relative R&D costs associated with technology nodes between 0.25μm and 45nm, shown in Fig. 1.1.10, have increased by over a factor of ten. The cost of a manufacturing facility has also escalated quickly, and is likely to be close to US$5B for the 45 nm node, for fabrication at an economically-competitive scale (Figure 1.1.11). Reduced manufacturing cost can be realized through a larger scale of manufacturing, implementation of state-of-the-art information technology, and use of automation systems in the manufacturing facilities, along with collaborations with equipment suppliers to improve tool performance and efficiency. The transition to 300mm wafers has significantly reduced wafer cost, and increased the potential for higher yield, and improved product quality. New 300mm facilities built and planned by TSMC will each have a capacity exceeding 100K 300mm wafers per month, when fully operational. Such "Giga-fabs" will not only have inherent cost advantages over smaller facilities, but will also help improve product quality, accelerate yield learning and time-to-volume, and minimize costly product re-qualification. In the past few years, TSMC has invested several hundred million dollars in information technology and automation systems, which have resulted in improved yield, shorter production-cycle time, and overall lower manufacturing cost. Going forward, foundries also need to further expand collaborations with equipment suppliers to ensure a competitive cost structure for new generations of process technology. Recent initiatives, embarked on by foundries in DFM (Design for Manufacturing) and DFT (Design for Test) are also intended to help reduce the overall die cost, from design to prototyping, to wafer manufacturing, and to test, assembly, and packaging.

e) Continuing R&D and Capital Investment

Finally, foundries need to be able to continue to invest in R&D to be amongst the leaders in industry introduction of the latest generation of process technology. Also, they will continue to invest in new production facilities; production capacity should continue to increase proportionately with overall revenue growth, reaching well above 30% of total world-wide silicon IC-wafer production by 2010. Silicon-based CMOS technology and Moore's Law will continue for many years to come. There are many opportunities for innovation in device structures and materials, but IC manufacturers must work closely with equipment vendors to contain costs. The foundry silicon-CMOS- technology platform also provides tremendous opportunities for nano-technology innovation, and business opportunities for the IC industry and for the ISSCC community. Foundries will enjoy symbiotic and sustainable growth with the rest of the IC industry in the 21st century by collaboration with, and virtual integration with, product and system companies, and with equipment and EDA suppliers, to contain the cost of continuing progress.

Forecast of Future Growth for the Foundry Segment

By adopting the strategies we have outlined in the previous sections, we believe it is possible to propel growth in the foundry segment, and so bolster overall IC industry growth. Evidence to support this assertion for foundry growth can be seen in wafer-production trends at TSMC, which are shown in Fig. 1.1.12. Despite the overall slowing of IC-industry growth, wafer production rates at TSMC have increased with technology progression.

The relative importance of the foundry segment to the IC industry as a whole will continue to increase, and the impact revenue (See Fig. 1.1.14) for the foundry segment should rise to nearly to 40% by 2010. Projections for revenue growth for the segment to 2010, and for foundry revenue relative to the IC industry, are shown in Figs 1.1.13 and 1.1.14 respectively.

Summary

Foundries are now an integral part of the overall semiconductor supply-chain, and there is every reason to anticipate that the importance of the foundry segment to the IC industry will increase further. Continued IC-industry growth will depend on the sustained growth of the foundry segment, and, here, we have outlined the key strategies needed to propel this growth.

We believe that foundries must expand into new CMOS-logic IC-product markets. But, foundries must also penetrate segments of the IC market that are currently not involved in foundry relationships, by broadening the range of technologies that are offered. In the future, therefore, foundry-market leaders such as TSMC will provide an increasingly broad portfolio of CMOS-derived technologies (such as, RF, mixed-signal, high-voltage, non-volatile-memory, embedded- DRAM, for example) concurrently with the design environment necessary to address issues in memory, analog, high-performance logic, or image-sensor applications.

One of the most important elements of future foundry success will be the ability of the foundry company to create a much deeper and broader relationship with each of its customers. Ideally, the customer should view the foundry like its own technology team, and its own fab. This new type of integrated relationship differs from many previous foundry-customer relationships, in that both design and technology engineering proceed concurrently from an early stage in the product-development effort. The success of this relationship will require a much greater information flow between the design and foundry teams, and concurrent optimization of both design and process technology, to meet product requirements. Such relationships can offer a significant advantage to customers in meeting product cost, performance, and time-to-market requirements.

Acknowledgments:

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References:

[1] Data after 2006 (Including 2006) – IC insights, The McClean Report 2006 Edition(Feb, 2006), Page 2-20, Figure 2-15. Data before 2005 – SIA statistics. (Actual shipment statistics maintained by SIA)

[2] Total IC: Data before 2006 – SIA statistics; Data after 2006 – IC Insights, The McClean Report 2006 Edition(Feb, 2006), page 2-32, Figure 2-26

[3] TSMC Internal Estimate

[4] Total Foundry: Data after 2000: IC Insights, The McClean Report 2006 Edition (August 2006 Update), Page 6, Figure 2; Data before 2000 – IC Insights, "The McClean Report", historical editions.

[5] IC Insights, The McClean Report 2006 Edition(Feb, 2006), Page 3-19, Figure 3-16

[6] IC Insights, The McClean Report 2006 Edition(Feb, 2006), Page 3-20, Figure 3-17

[7] Total Foundry: Data after 2000: IC Insights, The McClean Report 2006 Edition(Feb, 2006), Page 3-17, Figure3-14; Data before 2000: IC Insights, "The McClean Report" historical editions

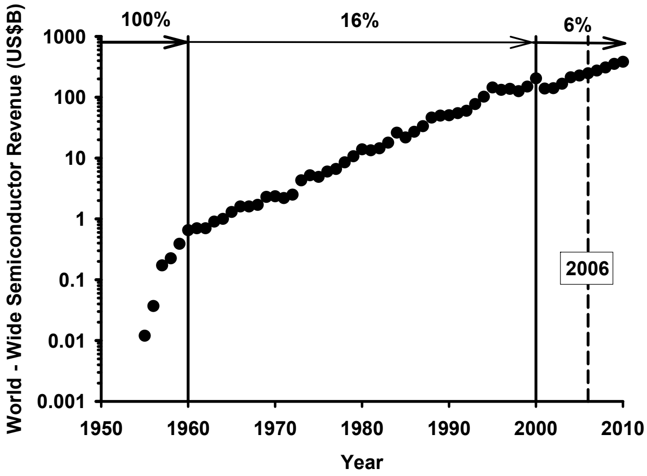

Figure 1.1.1: Historical and projected semiconductor IC revenues from 1955 to 2010[1]. Between 1960 and 2000, the industry grew at an annual rate of 16%. From 2000, the industry growth rate has slowed to 6%.

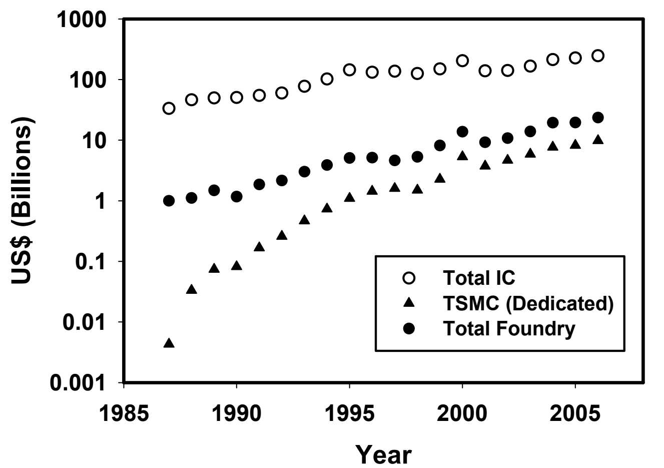

Figure 1.1.2: Comparison of total IC, total foundry, and TSMC revenues since the inception of TSMC in 1987[2,3,4].

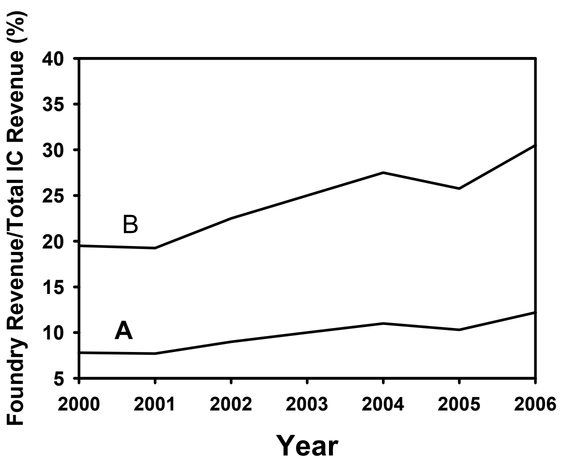

Figure 1.1.3: A: Direct foundry revenue relative to total IC revenue[5] and B: Total impact revenue of foundry-produced products relative to total IC revenue[3]. The latter indicates the estimated revenue from finished products derived from foundry wafers. TSMC estimates this revenue to be 2.5 times the foundry wafer revenue.

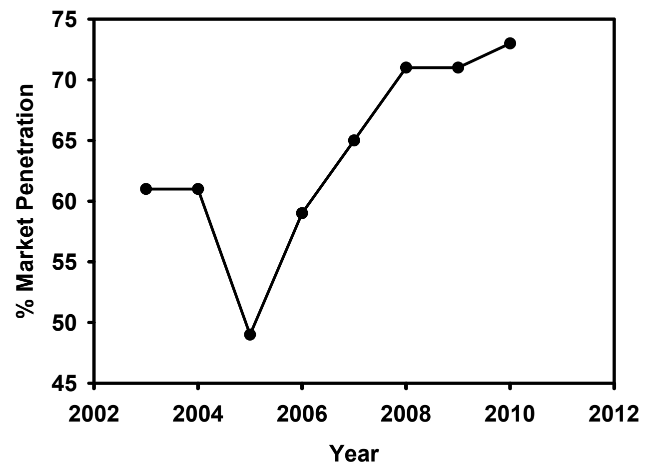

Figure 1.1.4: Actual and predicted (from 2006 onward) total foundry sales as a percentage of the CMOS logic market[6] (ASIC, PC-peripheral, Programmable logic).

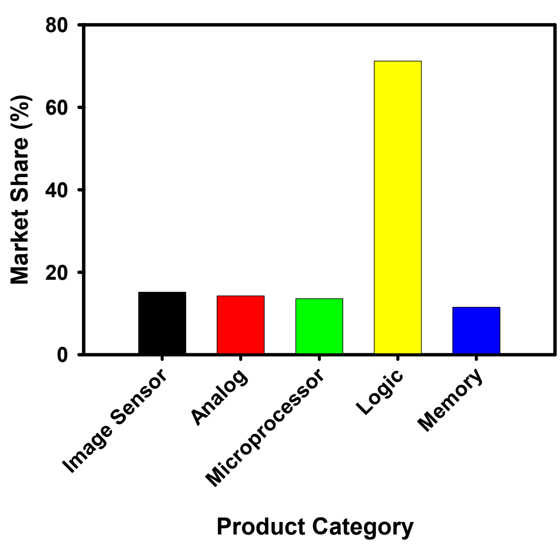

Figure 1.1.5: Foundry share of major IC market segments[3].

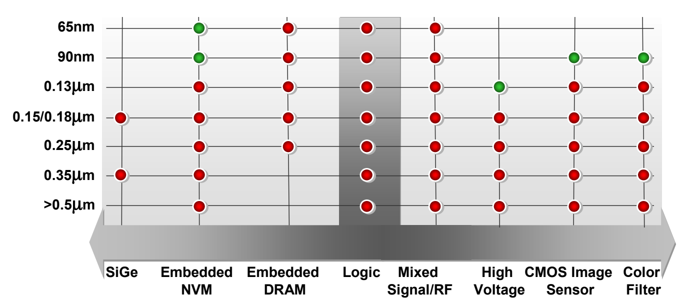

Figure 1.1.6: Technology offerings available at TSMC for each major technology node.

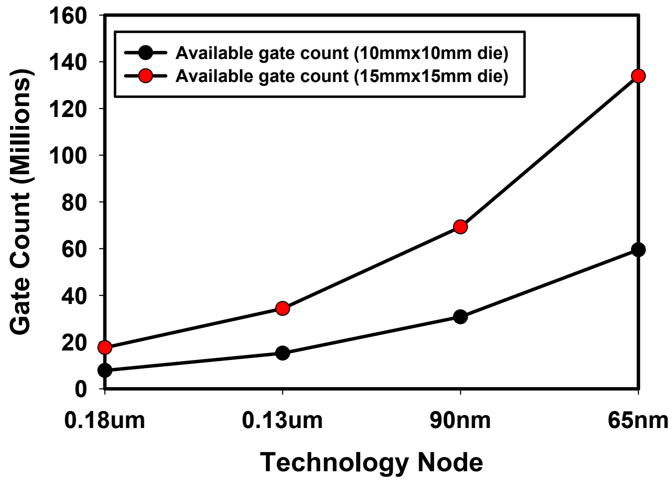

Figure 1.1.7: Transistor gate count trends versus technology node for a range of die size[3].

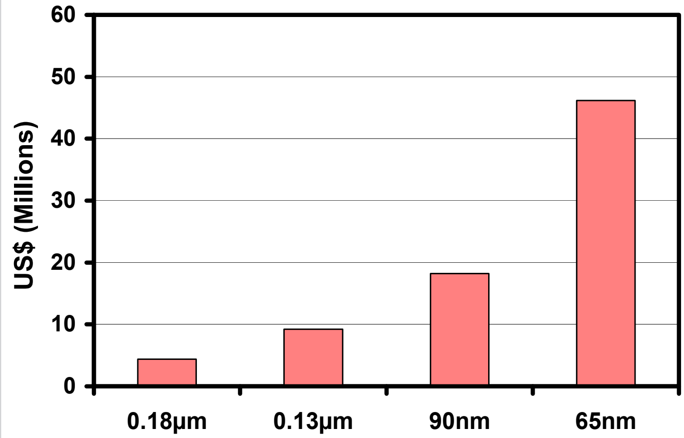

Figure 1.1.8: Design cost for typical CMOS logic-circuit design[3].

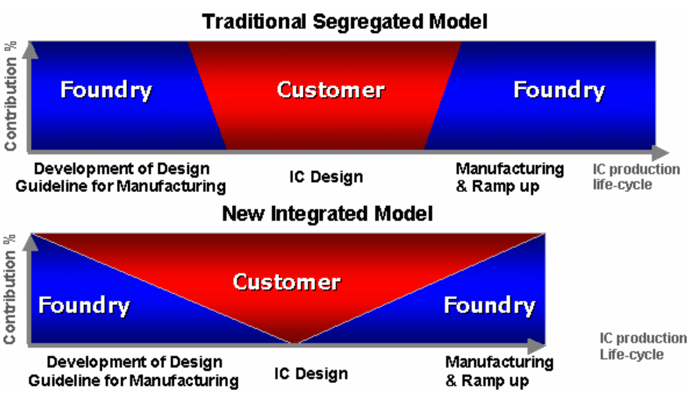

Figure 1.1.9: A new integrated interaction between the foundry and the customer design-team is required for future product success. With the new integrated model faster. time-to-market can be achieved, due to concurrent development.

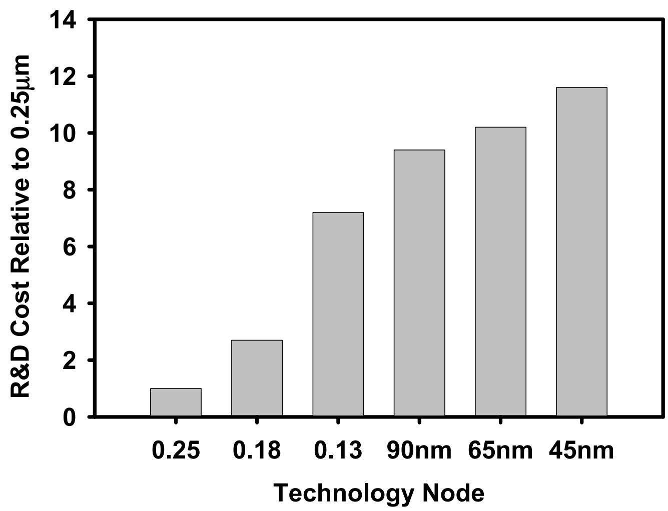

Figure 1.1.10: Total R&D costs versus technology node, relative to costs at 0.25µm[3].

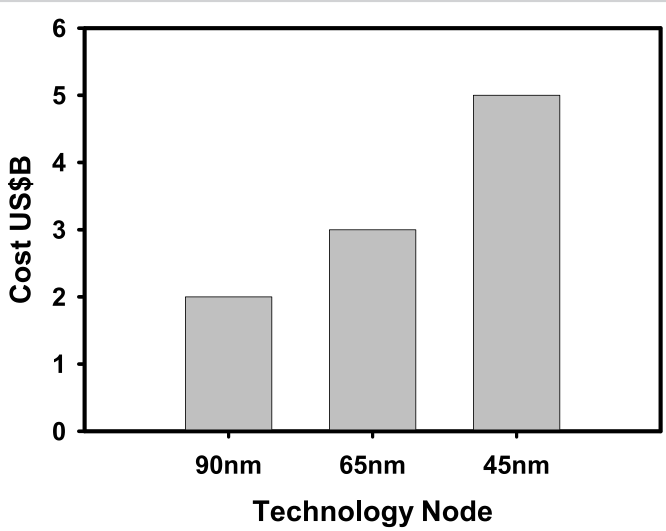

Figure 1.1.11: Costs to construct manufacturing facilities for advanced CMOS technologies[3].

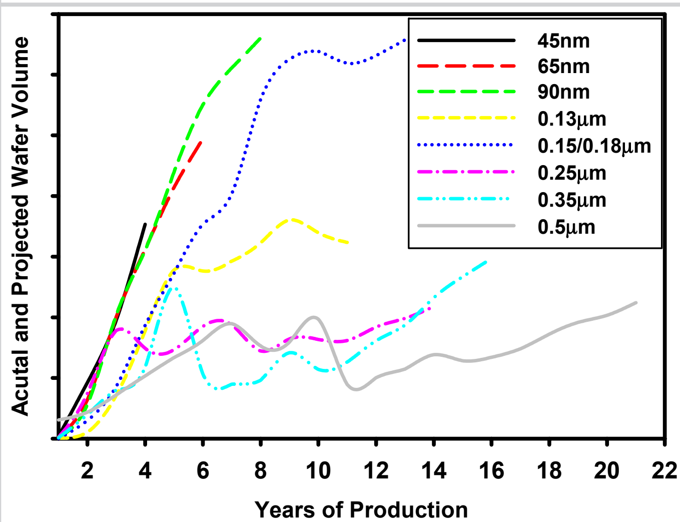

Figure 1.1.12: Actual and projected wafer volume as a function of time following technology introduction for foundry technologies at TSMC.

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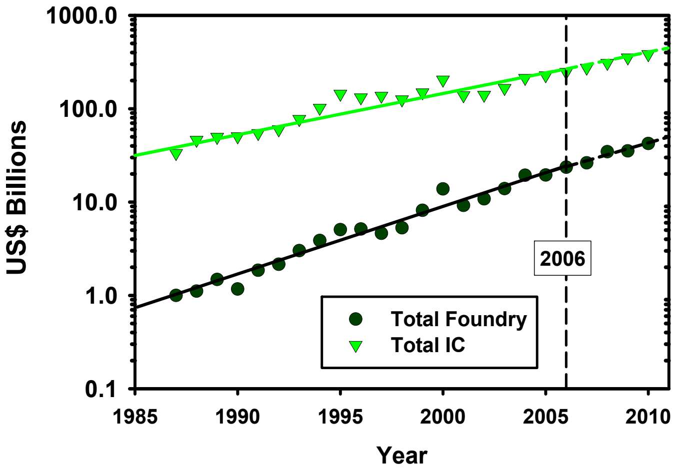

Figure 1.1.13: Total IC and foundry revenue projections from 2006 to 2010[2,7].

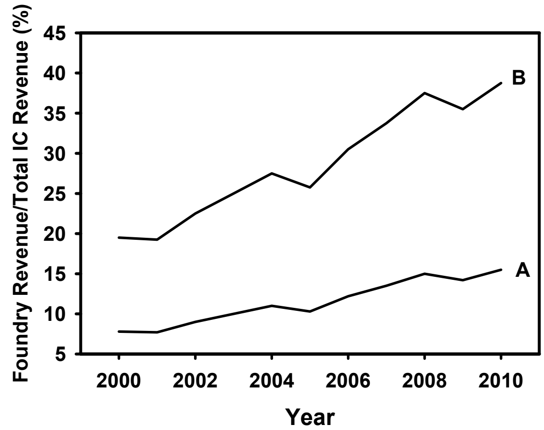

Figure 1.1.14: A: Projection of foundry revenue relative to total IC revenue, and B: projection of total impact revenue of foundry-produced product relative to total IC revenue. The latter indicates the estimated revenue of finished products derived from foundry wafers. TSMC estimates that revenue to be 2.5 times foundry wafer revenue.